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INFERENCE OF PROPERTIES OF THE EARTH FROM SATELLITE MEASUREMENTS OF INFRARED EMISSION

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Abstract

Important characteristics of the atmosphere and surface of a planet can be derived from the intensity and spectral variation of the emitted radiation. Two conditions must be fulfilled to uniquely relate the measured (remotely sensed) radiation quantities to the desired planetary parameters: 1) spacecraft and sensor instrumentation must provide for sufficient accuracy, resolution, calibration, and geographic coverage in the measurements; and 2) theoretical or empirical models must exist to permit rigorous analytical derivation of planetary parameters such as surface temperatures, soil conditions, or vegetation cover, etc. from the radiation measurements. Spacecraft techniques and systems are now under development to provide the measurements of emitted terrestrial infrared and microwave radiation. To infer Earth surface properties, it is necessary to critically examine the limitations imposed by this technology and by the physical relationships which must be utilized to make these inferences.

Introduction

The purpose of this presentation is to review the potential of using satellites for measuring characteristics of the earth's surface by observing emission of infrared radiation. This potential will be limited by technological requirements and by constraints imposed by the laws of physics. The emphasis will be placed on satellite observations, since surface based and aircraft observations already have been covered elsewhere.[1] There it has been demonstrated that characteristic signatures of the surface properties of the earth indeed can be measured by observations in the infrared emission spectrum. I shall attempt to show that in making such observations from a satellite one must consider two important points: the technological limitations imposed primarily by the spacecraft from which the observations are to

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be made; and the interference by the atmosphere, which affects the derivation of earth surface properties from the measured radiation quantities.

Technological limitations imposed by the spacecraft will affect the accuracy, spatial, and spectral resolutions of the measurements. Obviously, the spacecraft-sensory system must provide the appropriate technology to insure at least a minimum of such required accuracy and resolution.

Analytical and/or empirical models must be used to derive the desired geophysical properties (temperature, nature of surface, etc.) from the observed radiation quantities (radiance as a function of wavelength and/or angle). Such models generally involve the assumption of the validity of certain physical laws relating these quantities to each other. Above all, such models must account for the effect of the atmosphere upon the radiation emitted by the earth's surface. Depending on the spectral region of observation and on atmospheric conditions, e.g., cloudiness, water vapor concentration, etc., this effect of the atmosphere ranges from transparency to complete obscuration. Thus, the constraints imposed by spacecraft technology as well as by the physical properties of emitting surfaces and atmospheric absorption and reemission will be discussed in conjunction with a number of examples obtained from meteorological satellites with relatively simple instrumentation.

Technological Considerations

Ground-based, aircarft or balloon-borne remote sensing can be done with great accuracy and at very high spatial resolutions, because there it is easy to use large diameter optics and extremely sensitive radiometers with highly cooled detectors. In spacecraft applications, the use of optical systems larger than several inches in diameter and the use of cooled detectors each constitutes a major step forward in spacecraft technology. Early meteorological satellites such as TIROS have been able to accomodate multichannel mapping radiometers with optics diameters of about 2 in., using uncooled thermistor bolometers as detectors. In these spacecraft, the spin of the satellite was used to perform the scanning across the earth's surface in order to compose a radiometric image. Because such spacecraft maintain a fixed orientation in space and were not stabilized with respect to the center of the earth, composition of a contiguous image was extremely complex. Later spacecraft, such as Nimbus I and II, were stabilized in three axes, and continuously earth oriented. Optical systems of up to about 10 in. in diameter could be accomodated on Nimbus, although radiometers now flown on these spacecraft employ optics of less than half this size. Stabilization of Nimbus spacecraft also permitted the use of radiation cooled photodetectors. Temperatures of about 200°K have been achieved for the PbSe detector of the High Resolution

Infrared Radiometer (HRIR) operating in the 4-μ window on Nimbus I and II. Provision of full earth stabilization and increased weight, power, and viewing-space capacity of the Nimbus spacecraft, however, has brought with it an almost one order of magnitude increase in cost over the TIROS spacecraft. Within the next 5 years, spacecraft could accomodate radiometers and spectrometers with larger optics and cooled detectors at considerably lower temperatures. The Table 1 summarizes our present assessment of the state of technology.

From these considerations, it is obvious that the best spatial resolutions that can be achieved from orbit today are in the order of a few hundred meters. It must be noted that the limitations of spatial resolution are based only on the diffraction limit for radiation at 12.5μ. This implies that the angular resolution of the radiometer is given by the angular diameter of the Airy disk which is approximately 2.44 times the ratio of wavelength (λ) to optics diameter (D). To account for additional diffraction due to the obscuration by secondary optical elements we assumed, conservatively, that the angular resolution of the sensor, measured in radians, is given by: $5(\lambda/D)$.

We have not considered any constraints imposed by other engineering problems such as employing a properly cooled detector (77°K) with a Detectivity of at least 10^{10} cm Hz watts^{-1}. In the future, such as for the next five years, even using the most expensive available rocket boosters, we cannot expect spatial resolutions better than several tens of meters. Thus, it is fatuous to even discuss spatial resolutions of the order of fractions of meters, as has been suggested for the tracking of wildlife and other small targets by remote sensing from orbit. To achieve resolutions of this magnitude it would be necessary to fly telescopes of the size (or exceeding the size) of the Mt. Palomar Observatory!

If it is desired to use spectral emissivity in addition to temperature gradients for the mapping of surface characteristics, it is necessary to consider spectral resolution in addition to the spatial resolution limitations. Infrared spectrometers to accomplish such observations with relatively low spectral resolution have been flown on COSMOS satellites of the USSR.

Instruments with much higher spectral resolutions are now being built and are expected to be flown on Nimbus spacecraft in the very near future. These instruments may operate in the two window regions at 4 and 11μ, respectively, and can achieve a spectral resolution of 1:200, i.e., 5 cm^{-1} at 10μ. Mainly because of the sensitivity limit of the detector, the time required for one complete spectral scan is relatively long; approximately 10 sec/scan. Considering the motion of the spacecraft across the surface of the earth such scan time corresponds to a "smear" over an area of about 100 km. Thus, the maximum linear resolution achievable with present-day infrared

Table 1

Estimated mission cost, optics size capacity, and spatial resolution capability for remote sensing instrumentation on some presently conceived NASA spacecraft.

Spacecraft	Optics size, in.	Angular Resolution mrad	Linear resolution for orbit ht. of 1000 km (300 km) meters	Stabilization	Approximate cost, $mill.
Advanced TIROS	5	0.5	500 (150)	Stabilite[a]	10
Nimbus	10	0.25	250 (75)	3 axis active controls	40
Apollo(?)	36	0.075	75 (25)	Manned(?)	>100

[a]Spin stabilized by rapidly rotating wheel spinning in plane of orbit. Major portion of spacecraft is despun from wheel. Magnetic attitude control keeps wheel oriented in plane of orbit.

spectrometers is approximately 100 km. On future spacecraft, detectors may be cooled to temperatures of as low as 100°K by radiation or even to 25°K by cryogenic cooling. It will then be possible to improve the spectral resolution by at least one order of magnitude. However, in order to perform remote sensing of earth surface characteristics, it may not be necessary to achieve such high spectral resolutions and it may be more advantageous to use the signal to noise ratio gained by the colder detector to increase the scan speed, thus improving the spatial resolution. With such cooled detectors, increases in scan rates to as high as 10 scans/sec could be achieved. This would yield spatial resolutions of less than 1 km.

In addition to spatial and spectral resolution the question of coverage and data handling is of foremost importance in mapping the earth. It is obvious that, as requirements for spatial resolution increase, coverage requirements must be limited lest the problem of data storage on the spacecraft, data transmission to the ground, and data processing and display will by utterly overwhelming. For example, a high-resolution spectrometer would produce about 10^9 bits/orbit if it were operating for full earth coverage.

Therefore, from the point of view of technological limitations such as spacecraft stabilization, detector sensitivity, and, above all, spatial resolution, the prospects are very good for obtaining thermal maps of the surface of the earth for geological analyses, ice surveys, and oceanographic studies, for which large scale imaging of thermal gradients suffices. However, for detailed agricultural or forestry analysis, for which high spatial resolutions and very wide global coverage may be required, the technology imposes serious limitations. Examples for the observation of topographic and geological surface features with the relatively primitive thermal mapping devices employed in the 4-μ infrared window on Nimbus (HRIR) are shown in Figs. 1 and 2.

Considerations for the Derivation of Geophysical Quantities from Radiation Measurements

The simplest and most frequently used relationship between radiation properties measured from a spacecraft and the properties of a surface is Planck's law. This relates the radiation intensity measured within a given wavelength interval to the temperature and emissivity of a surface. Assumptions inherent in the application of this law are that the variation of the observed radiation intensity with angular direction is known and that the field of view of the satellite sensor is filled by a uniform surface. Thus, one may derive the surface temperature from such an intensity measurement, provided that the emissivity of the surface for the given wavelength interval is known. Or, one may measure the emissivity of such a surface in addition to its temperature by making spectrometric observations and derive characteristics

regarding the nature of the surface from the spectral emissivity characteristics. In all cases, however, one must account for the interference of the atmosphere with the radiation emitted by the surface and transmitted through the atmosphere.

In a clear atmosphere, three gases are responsible for absorption and remission of radiation emitted below the atmosphere: water vapor (6 to 7μ and longer than 16μ), carbon dioxide (4.3 to 6μ and 14 to 16μ), and ozone ($9.6\ \mu$). In the regions between 3.8 to 4μ and 10.5 to $12.5\ \mu$, the atmosphere is relatively clear of absorption by these constituents. Thus, these regions are identified as "windows" and will be most useful for detection of radiation properties of the underlying surfaces. Sensing of radiation intensities in the absorption regions of these three constituents also may provide valuable information on the characteristics of the atmosphere, such as temperature profiles, water vapor, and ozone content, and their distribution with height; however, the measurement of these properties is primarily of meteorological interest and is not within the scope of this paper.

Even in the two windows there is a residual absorption by water vapor, carbon dioxide, and ozone which must be corrected for if precise measurement of surface temperatures are to be made radiometrically. Computations for such corrections have been made for the 4 micron window used in the Nimbus HRIR observations and for the 8- to 12-μ observations used on TIROS by Kunde[2] and Wark,[3] respectively. Computations of these corrections are based partly on empirical models of the transfer of radiation through these gases and on the postulation of a knowledge of the concentration and distribution of these gases in the atmosphere. The magnitude of the corrections as a function of angle for the 1962 Standard Atmosphere[4] is shown in Fig. 3. Similar correction curves have been drawn for other reference atmospheres such as moist tropical, dry arctic and similar atmospheres.

The major obstacle to the remote detection of surface properties by sensing emitted radiation in the infrared is posed, however, not by these three absorbers for which corrections can be computed, but by clouds, fog haze, and particulate matter suspended in the atmosphere. In most cases, interference by these constituents cannot be computed and corrected for, since there are only very inadequate theoretical models for the transfer of radiation through fog, clouds, and haze and since the consistency and distribution of these interfering agents in the atmosphere is generally not known. Thus, observations can only be made and corrected for if the atmosphere is verified to be truly "clear." Figure 4 illustrates that many areas will not be clear when the satellite passes over. It shows an observation of the earth made from the ATS-I satellite covering an area from the China Sea on the left to the American Continent on the right and from the Gulf of Alaska on the top to Antarctica on the bottom. It is quite obvious that the areas of the earth which are completely cloud free

in this picture are small and few. This ATS picture as well as many other satellite observations and climatological records indicate that certain areas, such as Arctic regions, the tropics, and much of the midlatitude zones, will be cloud covered for a majority of the time; satellite passes over these areas would be required for an extended period in order to provide sporadic observations of the surface. The subtropical regions in which most of the deserts are located are generally cloud free and would, on the other hand, be considerably more accessible to remote sensing from satellites.

Spectrometric sensing appears to be quite promising on the basis of Laboratory and field measurements.[5,6] Here, however, one must keep in mind that the spectral features which would lead to the identification of an observed surface must lie in one of the two mentioned infrared windows. Superficial examination indicates that for many features this is not the case. In fact, many of the spectral features of minerals and rocks observed in the laboratory and in the field are attributed to the reststrahlen bands and overlap with the strong absorption band of atmospheric ozone at 9.6μ. Many other spectral features of minerals and soil, particularly those of hydration and carbonation coincide with the absorption bands of atmospheric water vapor and carbon dioxide (Fig. 5). Thus, the relatively narrow windows will permit observation of only few and not necessarily very exhaustive spectral surface features. Therefore, the hopes for "mineral prospecting" from satellites seem to be slim in the infrared emission spectrum.

Conclusions

Existing spacecraft technology and prospects for such technology to be developed during the next 5 years will permit the mapping of thermal features (surface temperatures and surface temperature gradients) on a global scale with a spatial resolution of a few hundred meters from satellites, primarily in the 10- to $12\text{-}\mu$ atmospheric window. Such mapping will be restricted to cloud free regions which will require a severe limitation on the geographic regions in which the mapping can be performed. Both the occurrence of cloud cover and the technological problem of data storage and display will limit the frequency and coverage for such observations over the entire earth. Rigorous analytical and empirical models must be developed to interpret such thermal maps with regard to the physical parameters to be derived. Many factors influence the thermal behavior of the surface of the earth and unique characteristics with regard to geology, ecology, etc., only can be derived after careful consideration of these various factors.

Thermal maps will be most useful in oceanographic analysis and in the study of polar ice distribution. In these cases the radiation maps can be interpreted directly in terms of the surface temperature

of the water and ice and such important features as the course of ocean currents (Fig. 6) or the patterns in the breakup of Antarctic ice may be derived, if cloud cover permits (Fig. 7). Overland interpretation will be more difficult. For example, Fig. 8 shows surface temperatures observed by the Nimbus I HRIR over the Siberian Tundra. It can be seen that the region to the North of 60° latitude is considerably warmer than the region to the south. The significance of this temperature gradient can only be assessed after careful examination of all contributing factors. In this particular case, knowledge of the meteorological situation in this area led to the conclusion that the warm surface temperatures north of 60° were caused by the advection of very warm surface air to the north of a frontal system indicated in the picture by the cloud band near 60° latitude. In contrast, the cold temperatures south of 60°N are due to the advection of cold polar air behind (south of) the front. These atmospheric temperatures sufficiently affected the soil temperatures to produce the temperature gradients observed by the satellite. Thus, in this case, the thermal features are unrelated to the surface itself, but rather a reflection of meteorological conditions prevailing over that area at that time.

Similarly, the thermal gradients indicated by the ward band around the Salar de Atacama shown in Fig. 2 could be an indication of a number of either geological, topographic or hydrological characteristics. When these gradients were consistently observed with Nimbus I they were initially assumed to be topographical features. Comparisons with topographic maps, however, showed that the warm band was at the same topographic elevation as the cold area in the center of the band. It was then assumed that the warm band might correspond to soil moisture, where water runoff, either on the surface or subterrainean, from the surrounding mountains would change the heat capacity of the ground to produce the observed temperature gradients. An aerial survey showed that the temperature gradients are most likely caused by deposition on the Salar of volcanic material eroding from the surrounding mountains. This material, which is of different geological origin than the salt bed itself, produces a contrast in thermal characteristics against the sintered salt in the center of the Salar: The absorption of sunlight and probably the emissivity for infrared radiation is much greater for the volcanic material than for the salt causing the volcanic material to show up "warmer" in the radiation map. A similar reasoning holds for the thermal contrasts shown near the Pie de Palo mountains observed also in Fig. 2. These are typical examples for the necessity of physical models in order to infer the composition of the soil from the thermal maps.

Analogous observations with regard to spectral variations of emitted radiation do not yet exist from satellites. However, even on the basis of the rather coarse thermal maps shown in the figures, one can conclude that more intensive analyses and especially, more

field experiments including perhaps, simple, exploratory spacecraft observations are necessary to exploit this method for mapping the earth's surface in the infrared emission spectrum. Only on the basis of such analyses and field experiments may one infer the geology, topography, ecology, etc. from features observed by satellites. Operational use of the exceedingly expensive spacecraft technology expected to be available in the near future should be contingent on the prior conclusion of such experiments.

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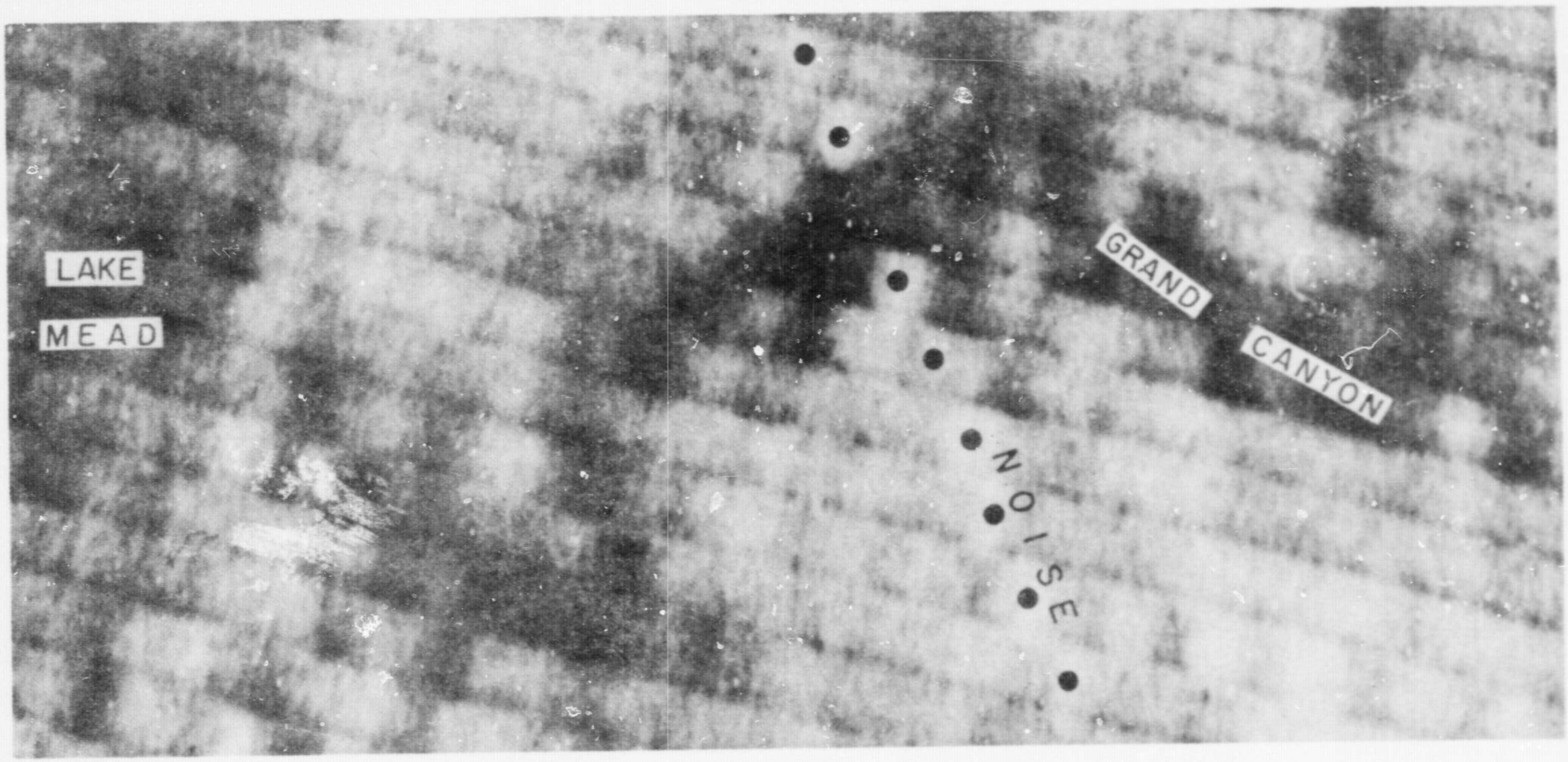

Figure 1a–NIMBUS I HRIR radiation picture made of Grand Canyon and Lake Mead area. Black dots represent periodic noise which should be disregarded.

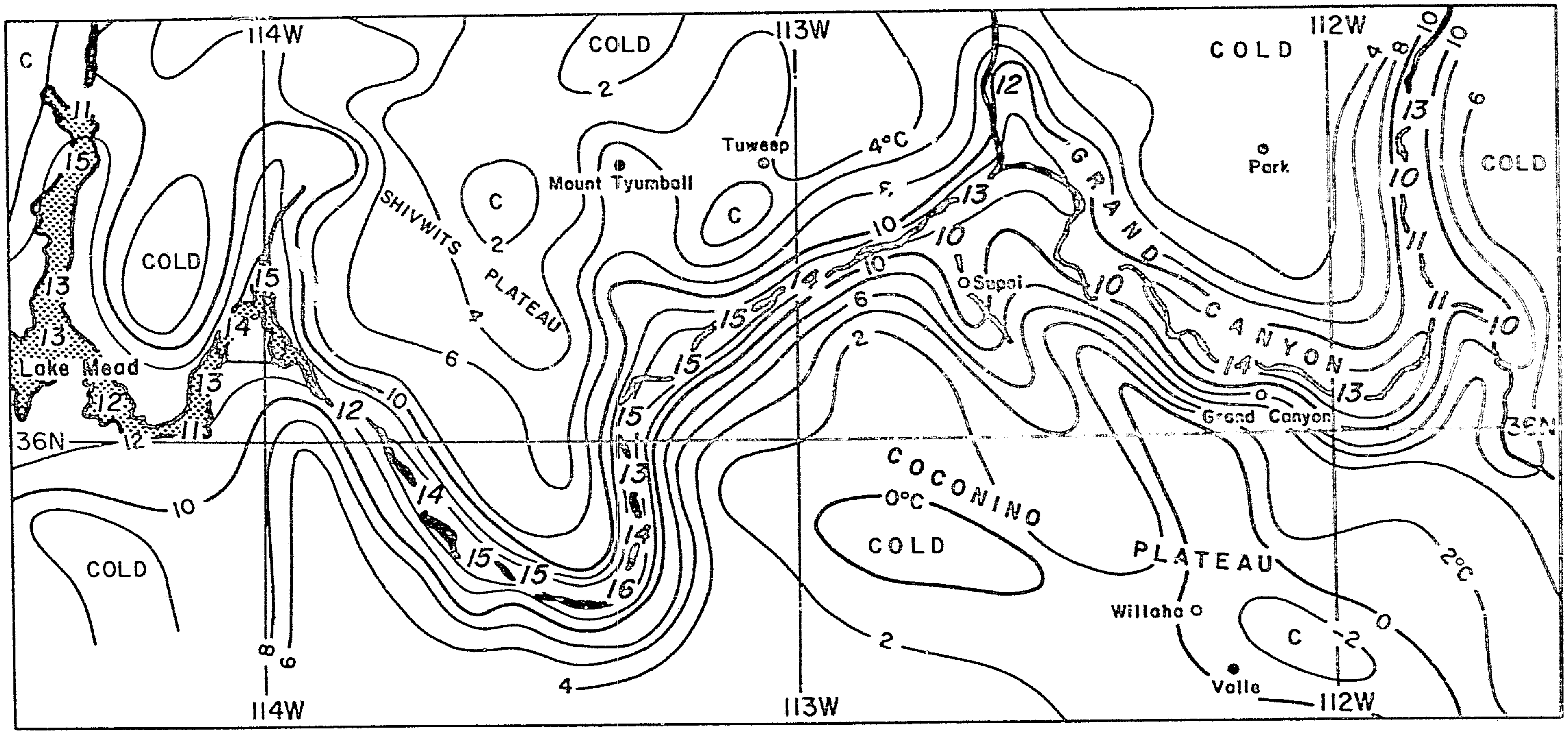

Figure 1b–Digital rendition of results shown in Figure 1a. Canyon Floor and Lake Mead temperatures are indicated by slant letters. Equivalent blackbody temperature of the canyon rim and plateau is shown by the isotherms contoured for every 2°C.

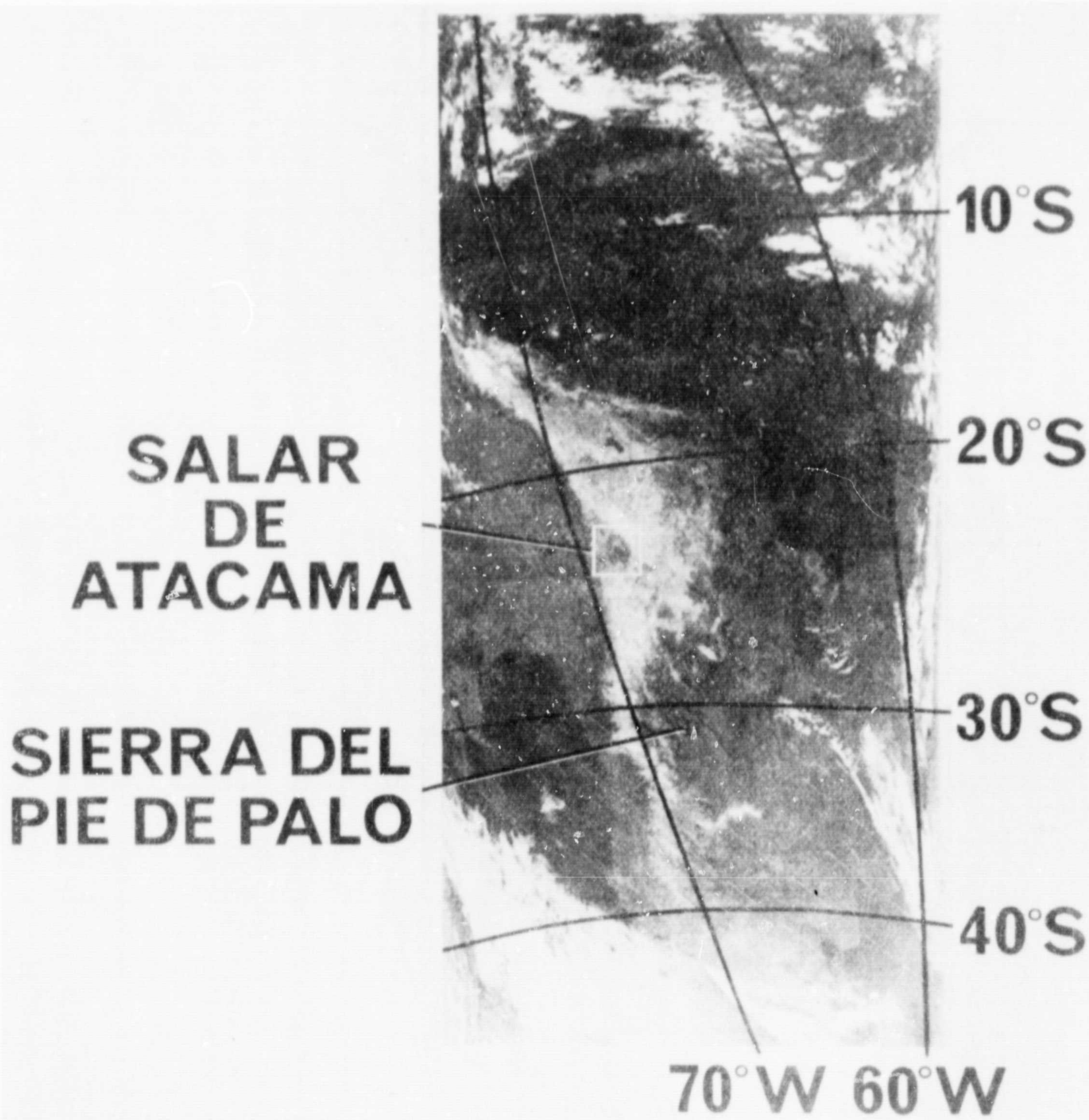

Figure 2–Nimbus I HRIR radiation picture made from above South America at about midnight on 13 September 1964. Black shades indicate warm, white shades are cold.

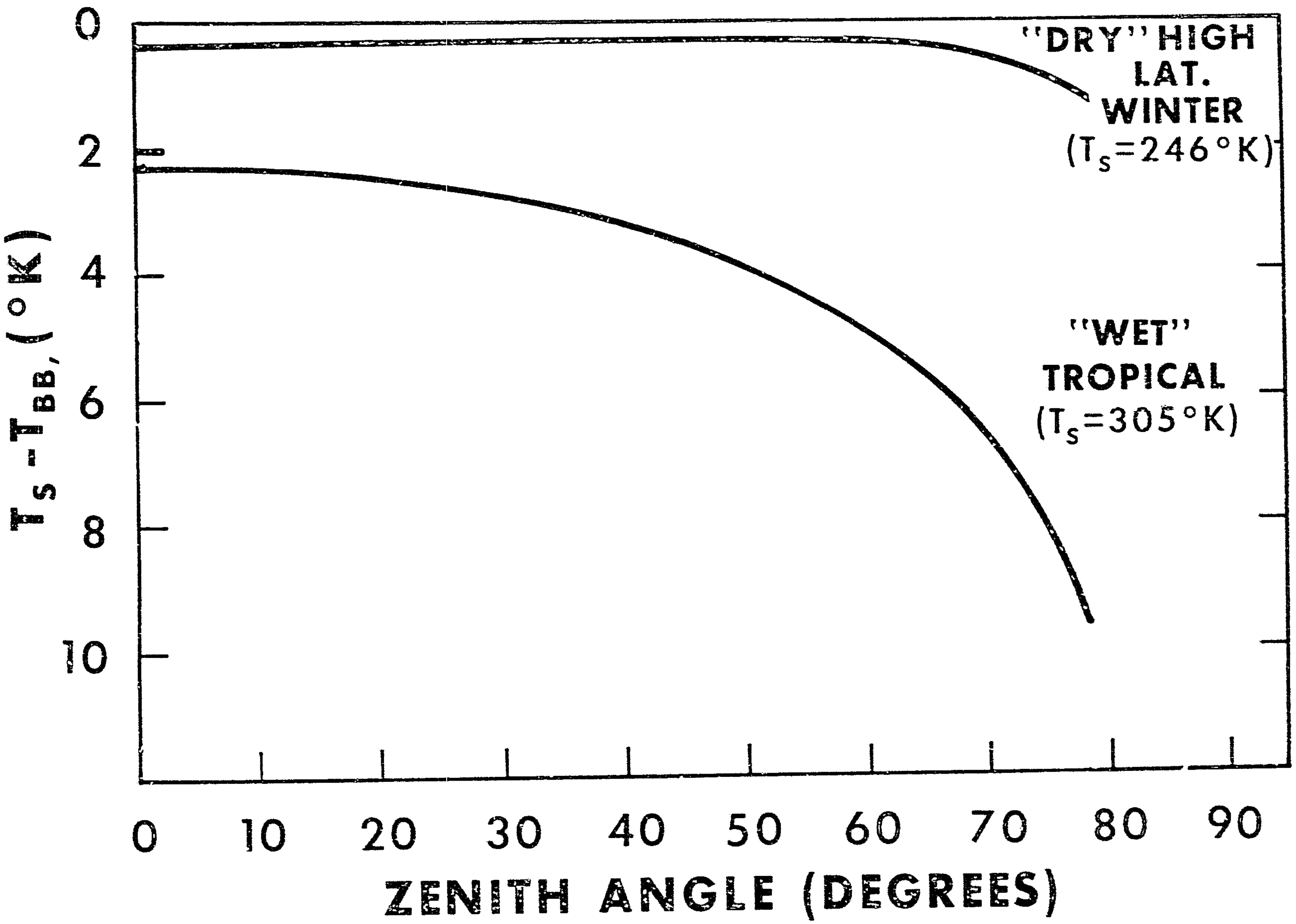

Figure 3—Theoretical surface temperature minus HRIR equivalent blackbody temperature difference as a function of zenith angle. A graybody surface emissivity of unity and clear sky conditions have been assumed (Ref. 3, p. 32).

Figure 4–Cloud cover observed by a scannint photometer aboard ATS-1 satellite over the Pacific Ocean on December 11, 1966. The view extends from about 60°N to 60°S (top to bottom) and from the South China Sea (left) to the Atlantic Ocean (right). Cloud formations associated with major storms can be seen over eastern North America, the North Pacific Ocean, and the South Pacific Ocean. The peninsula of Southern California and the Southwestern United States and Mexico can be recognized in the cloud free area. This observation was conducted by V. E. Suomi, Univ. of Wisc.

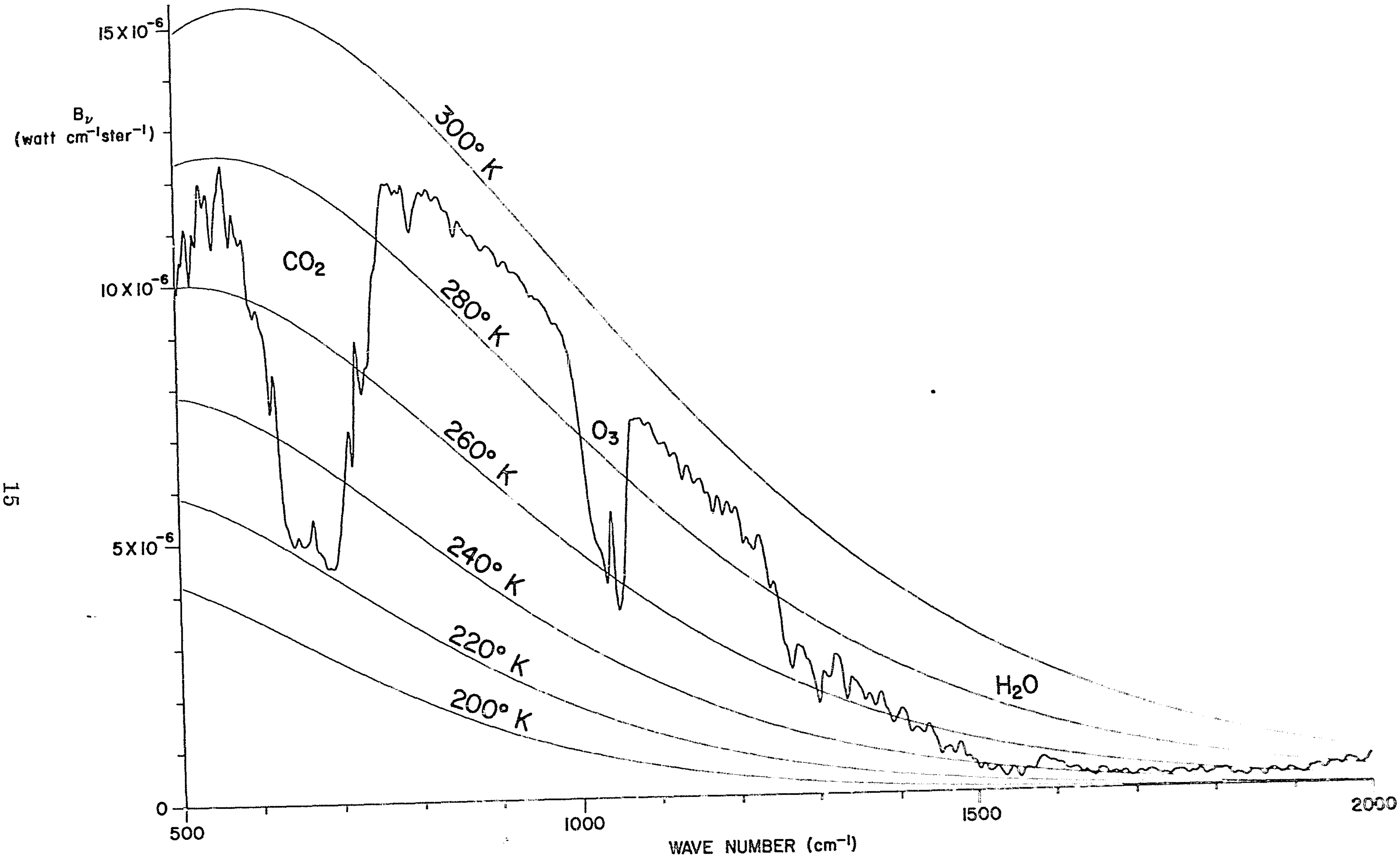

Figure 5–Spectrum of the atmosphere obtained with an Infrared Interferometer Spectrometer from a balloon at an altitude of about 31 km over Texas, May 1966. The measurement was provided by R. A. Hanel, Goddard Space Flight Center and L. Chaney, Univ. of Michigan.

Figure 6–Nimbus II HRIR observation of the Gulf Stream near local midnight on 2 June 1966. The Gulf Stream is represented by the dark streak of warm water (298°K) in the upper left stretching from southwest to northeast. The streak is bounded sharply by colder water on the left. On the right, the boundary toward the colder water is more gradual. The number in the center refers to 30°N, 292°E. The land mass of the Eastern Seaboard of the United States is differentiated from the water by still colder temperatures (very light shades) along the left edge of the picture. At midnight the land mass is much colder than the water. A cloud band extends from north to south through the center of the picture.

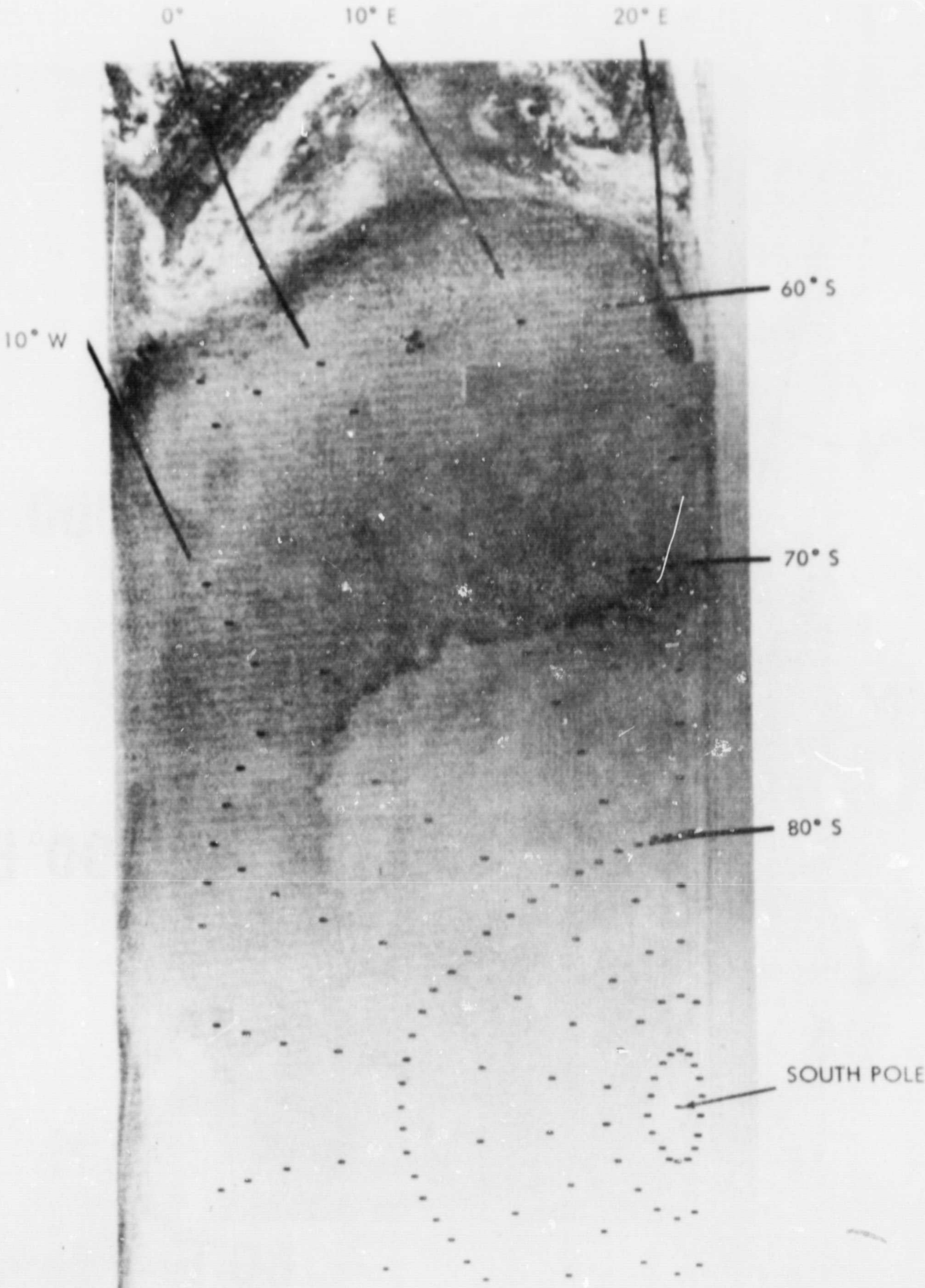

Figure 7—Nimbus I HRIR radiation picture made from above Antarctica at about midnight on August 29, 1964. Cold temperatures (ice) are white, warmer temperatures (water) are dark.

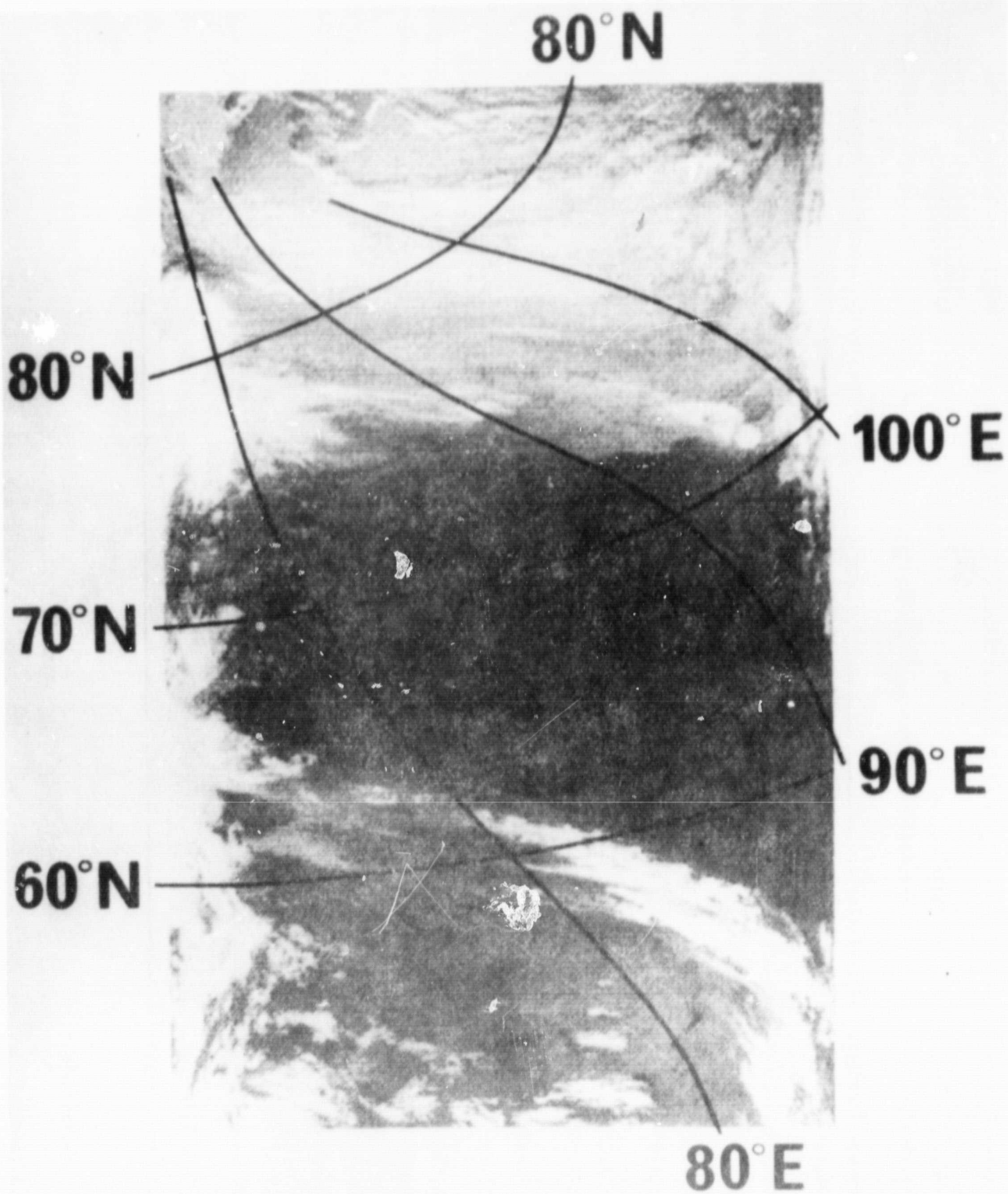

Figure 8—Temperature over Siberia observed by HRIR near midnight on September 5, 1964 (dark shades are warm, white shades are cold).